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Experimental research of thermal comfort conditions in small test buildings with different types of heating

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Abstract

The aim of this study is detailed analysis of long-term monitoring data of thermal comfort conditions and energy efficiency in small test buildings equipped with different heating systems. Calculations of PPD index and local thermal discomfort factors are provided for the test buildings during three weeks of heating season. It is shown that the type of heating system has influence not only on heating energy need, but also on thermal comfort conditions in the room.

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Keywords: Test buildings, thermal comfort, PPD, heating systems

1. Introduction

Five experimental test buildings with internal dimensions 3×3×3 m have been built in Riga, Latvia (Fig. 1). They have identical building constructions (floor, ceiling, door, and window) except outer walls for which different mainly regional building materials are used, the buildings are named after the main outer wall material - AER, CER, EXP, LOG, PLY (see more in [1]). It is important to note that materials thicknesses for the walls are chosen in such a way to get the same calculated thermal resistance (*U*-value) for all the buildings structures. After first 2 years of project running huge amount of data is collected and results (mainly about energy consumption for heating/cooling and humidity monitoring/modelling) are published [1-5].

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Fig. 1. Test buildings.

In the initial period buildings were equipped with identical air-air heat pumps, but in year 2014 the buildings were additionally equipped with different heating and cooling systems to perform detailed analysis of energy efficiency and their potential impact on temperature distribution and thereby also the thermal comfort conditions in a room. As heating season is still ongoing at the publication date, indicators of heat pumps' energy efficiency are only approximate. However, the three weeks data of indoor thermal conditions is enough to analyze the differences in thermal comfort conditions (PMV and PPD indices, see [6]) depending on local discomfort factors (vertical temperature difference and draught rate) for heating system under real operating conditions.

2. Experimental setup

Three new types of different heating systems are installed before 2014 heating season in the test buildings, replacing existing ones; as a result four types of heating systems (Fig. 2) are running and long-term monitored:

- a standard electric convectors heater near the window which is used as a reference (type EL, installed in building CER);
- an air-air heat pump (type A-A, installed in buildings AER and LOG);
- an air-water heat pump with water storage tank and low-temperature large-sized convectors placed on the floor near outer wall (type A-W.F, installed in building PLY);
- an air-water heat pump with water storage tank and heating capillary mats on the ceiling (type A-W.C, installed in building EXP

Measurements of electric/heating powers and integral energy consumption for heating systems, temperatures and humidity in the room at different heights, as well as outside air parameters (temperature, humidity, solar irradiation, etc.) are recorded every minute during long-term monitoring. A placement of main temperature/humidity sensors is shown on Fig. 3. Additional to fixed sensors mean radiant temperature has been periodically evaluated using portable microclimate measuring device *DeltaOHM HD 32.1*.

Fig. 2. Different heating systems installed in test buildings (from left to right): electric heater, air-air heat pump, air-water heat pump with convectors, air-water heat pump with capillary mats on the ceiling.

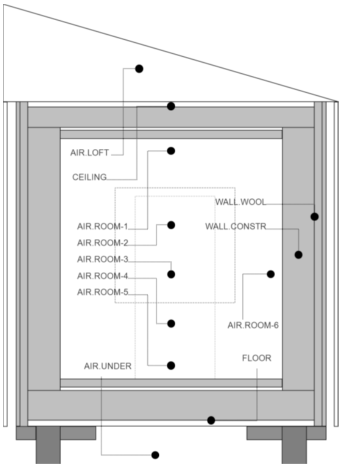

Fig. 3. Location of main temperature sensors in a test building.

Fig. 4. Microclimate measuring device *DeltaOHM HD 32.1*.

3. Methods

3.1. Thermal comfort parameters

The type of heating system, the placement of a heater (heat exchanger) and corresponding different air movement regimes influence the temperature distribution (stratification) in the room, which is connected with the thermal comfort conditions in a room and local discomfort indicators.

The method described in LVS EN ISO 7730 standard [6] (hereinafter ISO 7730) is based on the determination of the predicted mean vote index (hereinafter PMV) calculated from an equation of thermal balance for the human body. The value of this index is calculated by taking into account internal heat production in the body and loss of the heat to the environment. Four measured environmental parameters – air temperature, mean radiant temperature, air velocity, air relative humidity, as well as two estimated factors – human metabolic rate (*met*) and clothing insulation (*clo*) are needed to calculate the PMV. The last 2 parameters generally are unknown, but we will use for further calculations values according to sedentary activities (*met*=1.2) during heating season (*clo*=1) [6]. The other index proposed in ISO 7730 is predicted percentage of dissatisfied people (hereinafter PPD) that quantifies the expected percentage of dissatisfied people in a given thermal environment.

According to ISO 7730, the desired thermal environment for a space may be selected from among 3 categories – A, B and C (Table 1). Each category prescribes a maximum percentage of dissatisfied people (PPD) for the body as a whole and local percentage dissatisfied (PD) for local discomfort. We will calculate and analyze in our study PPD index and two of local discomfort parameters – draught rate (DR) and PD caused by vertical temperature difference between head (1.1 m) and ankles (0.1 m) for sitting person. Other local discomfort parameters – warm/cool floor and radiant asymmetry is not so important in our case. All calculations are made according equations from standard.

Table 1. Categories of thermal environment according ISO 7730.

Category	Thermal state of the body as a whole		Local discomfort			
	PPD, %	PMV	Draught rate, %	PD, % caused by: vertical air temperature difference	warm/cool floor	radiant asymmetry
A	< 6	-0,2 < PMV < 0,2	< 10	< 3	< 10	< 5
B	< 10	-0,5 < PMV < 0,5	< 20	< 5	< 10	< 5
C	< 15	-0,7 < PMV < 0,7	< 30	< 10	< 15	< 10

3.2. Energy efficiency calculations

The widely used coefficient of performance (or COP) of a heat pump is a ratio of heating/cooling energy provided to electric energy consumed including energy consumption of all auxiliaries. Declared heat pump COP is the value at fixed outdoor temperature +7°C, therefore different climate conditions (especially absolute temperature and relative temperature [7]), building characteristics and system's settings result in different actual efficiency values during the year. The seasonal coefficient of performance (SCOP) ratio is defined by standard [8] and describes the average annual efficiency. The heating period is divided in hour long periods with different temperatures and COP values are calculated for each of this period to find average value.

In this paper the actual energy efficiency ratio (hereinafter AEER) is calculated and analyzed for different heating systems installed in the test buildings. As the COP and SCOP ratios are standardized values, but actual energy efficiency ratio shows the real efficiency for particular set of heat pump system, heat exchangers and settings used, lower ratios are expected. Analysis of electric energy consumption for different heating systems used for the buildings with the same thermal properties allows calculating the AEER for investigated system under real operation conditions. Analysis includes electric energy consumption for heating and for internal sources like data loggers, sensors and other devices that work as internal heat sources. Ventilation energy consumption can be ignored, because this energy is released by a fan outside. Comparative calculations of measured electric energy are used for analysis of AEER for heating systems from November 2014 to January 2015.

4. Results

4.1. Thermal comfort parameters

The comparison of calculated PPD indices for all test buildings shows that it is very similar in four buildings (AER, CER, EXP and LOG) with totally various heating systems (Fig. 5). It means than all the installed heating systems can provide the same thermal comfort for the similar buildings. The only exception is air-water heat pump with convectors (type A-W.C,) installed in PLY test building. The reason of this is specific temperature regulation regime for this system, which provides a higher temperature difference between switch-on and switch-off. On the other hand high temperature difference means greater efficiency for this system (see next chapter), because heat pump turns on not so often.

Comparing the PPD indices (Fig. 6) with defined categories of thermal environment (Table 1), it is seen that in the beginning of measurements the conditions in all the buildings (except PLY) meet the B category requirements. However, decreasing of outside temperature at the end of December influences thermal conditions in AER, CER, EXP and LOG buildings to C category. At this time conditions in PLY building does not meet even requirements of C category thermal environment.

Comparison of PPD indices for all the installed heating systems depending on outside and inside temperature in shown on Fig. 6. It is clearly seen, that outside temperature practically does not have an influence on thermal comfort for different heating systems, exclude PLY building due to large temperature amplitude.

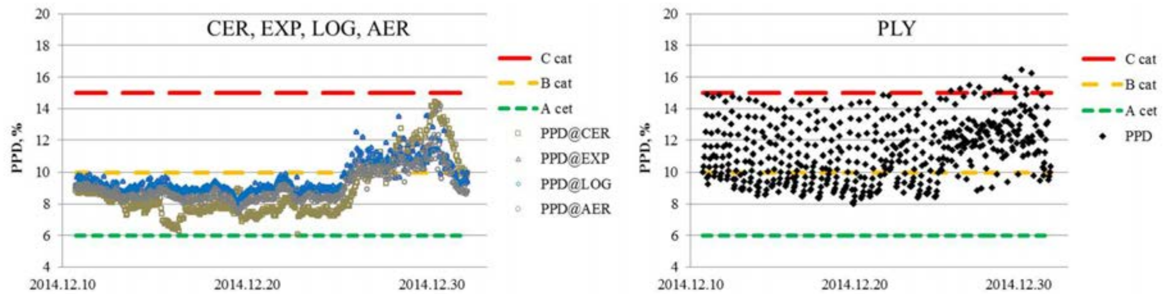

Fig. 5. Calculated PPD indices and its limits for three categories of thermal environment for different heating systems installed in test buildings.

Analysis of local discomfort in test buildings includes two parameters – discomfort due to draught rate (DR) and due to vertical temperature difference for sitting person. The first one is calculated using value of 40% for local turbulence intensity; results are visualized on Fig. 7. As it is seen, practically all the data points are below 6% level, which corresponds to A category of thermal environment (see Table 1). Another local discomfort factor PD caused by vertical air temperature difference in the middle of a room is calculated for sitting person and visualized on Fig. 8. Also in this case requirements of A category thermal environment are fulfilled, does not exceeding 1%. It should be noted that minimal temperature difference and corresponding PD value are observed in EXP and PLY building with air-water heat pumps, it is the result of low temperature heat carrier (water) and good air homogenization in the rooms excepting slight hot air layer near the heating capillary mats on ceiling in EXP building.

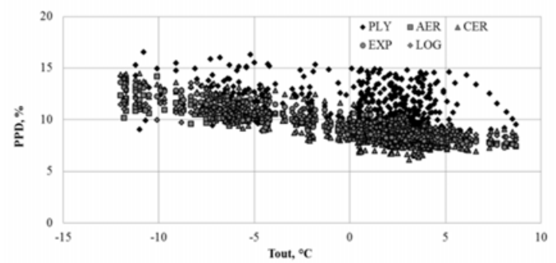

Fig. 6. PPD depending on outside temperatures for different heating systems during monitoring period.

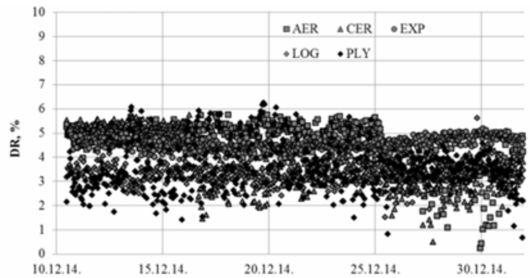

Fig. 7. Local discomfort by draught rate (DR) for different heating systems during monitoring period.

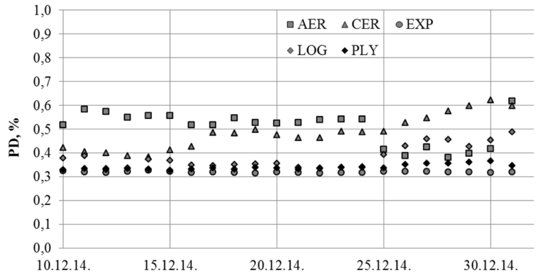

Fig. 8. Local discomfort caused by vertical air temperature difference (daily averaged data).

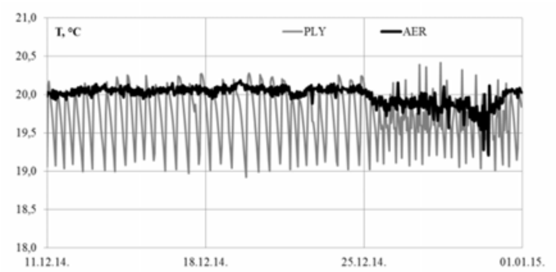

Fig. 9. Indoor temperature fluctuation in the middle of the room for heating systems A-W.F (PLY building) and A-A (AER building).

4.2. Energy efficiency calculations

Calculated actual energy efficiency ratios (see Table 2) based on measured electric energy consumption show that air-water heat pump (type A-W.F) in PLY test building works with highest efficiency ratio, but air-water heat pump (type A-W.C) in EXP test house with the lowest one. Such a high ratio for A-W.F heating system can be explained mainly by the water temperature settings, which are set in an unusually wide range allowing cooling down of the water by 1.3 °C (see Fig. 9). At the same time setting for all other heating systems provides temperature fluctuation typically less than 0.2-0.3 °C. E.g. air-air heat pump installed in AER building provides approx. 0.1 °C temperature fluctuations during first weeks of December 2014 (Fig. 9).

The results obtained for months with the outdoor air temperature below 0°C show that heat pump's A-W.C AEER is below 1, meaning that this system was working even below efficiency ratio for electric heater. It can be explained by large proportion of heat losses from heat pump system's outer block. Because of low temperature settings and specific construction –capillary heat exchanger system near ceiling, heat pump in EXP test building isn't working efficiency in winter period. Optimization of a temperature settings and minimization of heat losses from outer parts of this system can help to improve its efficiency. Air-air heat pumps work with AEER ratios that still are few times lower than defined COP value, which may exceed value of 5 for modern systems [9].

Table 2. Actual energy efficiency ratio for each month and test building/heating systems.

Test building	AER	CER	EXP	LOG	PLY	Time period	Average outside temperature
Heating system	A-A	EL	A-W.C	A-A	A-W.F		
Actual energy efficiency ratio	1.4	1.0	1.07	1.4	2.5	November 2014	+3°C
	1.7	1.0	0.93	1.7	2.3	December 2014	-0.4°C
	1.7	1.0	0.94	1.7	2.5	January 2015	-0.2°C

5. Discussion and conclusions

Long-term monitoring of thermal comfort conditions in the similar test buildings equipped with different heating systems allows analysing an impact of heating system's properties and its settings on thermal comfort conditions, which helps to find possible causes of the local discomfort and experimentally estimate the category of provided thermal environment according ISO 7730. Our study shows that totally different heating systems with standard settings provide the same level of thermal comfort and it is high dependent on environmental parameters (e.g. inside or outside temperature). Lower category of thermal environment is observed in the room when heating system is adjusted to allowing wide range of heat carrier's temperature; on the other hand this approach may be used to increase the efficiency of equipment due to less frequent operation. Thus, the balance between thermal comfort and energy efficiency (i.e. running cost) can be adjusted in a necessary direction.

All the heat pumps used in our experiment are over dimensioned for such small test houses with internal volume of 27 m^3, but the results are still reliable for comparable qualitative analysis and for future research with different heating systems and their set-ups and settings, as well as type of heat exchangers and heat carriers. Calculated actual energy efficiency ratios are several times lower than standardized COP and SCOP values and show a real electric energy usage to provide the heating. In this research actual energy efficiency of heat pumps depends on heat exchange system properties and settings, that is why results can be used for all heating system set analyse only

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